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Title of Invention : DISK DRIVE PROVIDED WITH IMPROVED RESISTANCE AGAINST MECHANICAL SHOCKS

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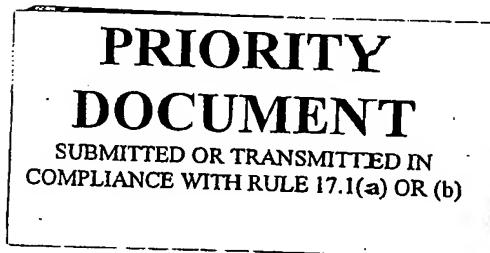
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PCT REQUEST

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0-2	International Filing Date	19 DEC 2002 (19-12-02)
0-3	Name of receiving Office and "PCT International Application"	REGISTRY OF PATENTS (SINGAPORE) PCT INTERNATIONAL APPLICATION

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0-4-1	Prepared using	PCT-EASY Version 2.92 (updated 01.10.2002)
0-5	Petition	
	The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty	
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I	Title of Invention	DISK DRIVE PROVIDED WITH IMPROVED RESISTANCE AGAINST MECHANICAL SHOCKS
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V	Designation of States	
V-1	Regional Patent (other kinds of protection or treatment, if any, are specified between parentheses after the designation(s) concerned)	EP: AT BE CH&LI CY DE DK ES FI FR GB GR IE IT LU MC NL PT SE TR and any other State which is a Contracting State of the European Patent Convention and of the PCT (except BG CZ EE SK)
V-2	National Patent (other kinds of protection or treatment, if any, are specified between parentheses after the designation(s) concerned)	SG
V-5	Precautionary Designation Statement In addition to the designations made under items V-1, V-2 and V-3, the applicant also makes under Rule 4.9(b) all designations which would be permitted under the PCT except any designation(s) of the State(s) indicated under item V-6 below. The applicant declares that those additional designations are subject to confirmation and that any designation which is not confirmed before the expiration of 15 months from the priority date is to be regarded as withdrawn by the applicant at the expiration of that time limit.	
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VI	Priority claim	NONE
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VIII-1	Declaration as to the identity of the inventor	–	
VIII-2	Declaration as to the applicant's entitlement, as at the international filing date, to apply for and be granted a patent	–	
VIII-3	Declaration as to the applicant's entitlement, as at the international filing date, to claim the priority of the earlier application	–	
VIII-4	Declaration of inventorship (only for the purposes of the designation of the United States of America)	–	
VIII-5	Declaration as to non-prejudicial disclosures or exceptions to lack of novelty	–	

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IX-1	Request (including declaration sheets)	3	–
IX-2	Description	14	–
IX-3	Claims	1	–
IX-4	Abstract	0	–
IX-5	Drawings	0	–
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	Accompanying items	paper document(s) attached	electronic file(s) attached
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IX-11	Copy of general power of attorney	✓	-
IX-17	PCT-EASY diskette	-	Diskette
IX-19	Figure of the drawings which should accompany the abstract		
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X-1	Name (LAST, First)	VAN DER VEER, Johannis, L.	
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10-6	Transmittal of search copy delayed until search fee is paid	

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Disk drive provided with improved resistance against mechanical shocks

The invention relates to a disk drive apparatus provided with means for reducing the disadvantageous effects of shocks.

As one of the importance quality ratings for the compact disc system, lots of effort have been put in practice to improve the system shock immunity (operational anti-
5   shock performance) with the lowest cost, especially, for optical data drives, portable, Car CD/DVD players etc.

In this invention, a novel controller based on the sliding mode control technique is developed to control the radial actuator fine displacement instead of the normal PID controller with improved tracking shock performance without critical requirement of
10   accurate shock detection. The same method can be applied to the focus actuator control also.

A general way to obtain sufficient shock immunity in the present commercial products is to use lower damping suspensions with higher servo gain at the lower frequency. side. However, the suspension design depends not only on the drive operational shock sensitivity but also on the suspension performance and dynamic range under all
15   circumstances during operating, handling and transportation, and material cost, mechanical design tolerances etc,. The lowering of the suspension damping rate to increase the shock immunity level is very much limited from the system point of view. Further more, the robustness to external shock by increasing the servo gain is also limited by the system stability requirements. A lower gain is also preferred to meet the design criteria of
20 .   measurement noise rejection or to get less sensitivity to certain disc defects during playing.

To achieve shock immunity level, some companies use the switching control technique in their servo control system. Upon the occurrence of shock, a higher servo loop gain with higher lag filter is used. When the position error is less than a certain threshold, both the servo loop gain and the lag filter are switched back to the normal playing values.
25   Effective application of this method to suppress shock requires accurate detection of shock. Application of a shock sensor is a direct method for accurate shock detection. But again this will increase the product cost. Again the system requirements of stability will also limit the shock performance improvement.

Some earlier investigations on the anti-shock system design for the Car CD system employed the acceleration feed forward filter to both focus and radial servo loop to counteract the original disturbances. The mute-level (i.e. the insensitivity to the external mechanical disturbance) could be improved by 10-40%. Considering the non-linear

5   disturbance coming from the mechanism, in combination with the acceleration feed forward filter, a number of modifications on the mechanism like pre-loading the upper porous bearing of the disc motor were implemented and the mute level could be increased by a factor of 2. Up to now investigations carried out with shocks showed that the most critical direction is the radial direction. A steel wire spring which pushes on the motor shaft via a delrin seat is

10   generally used as a practical solution to apply a radial load on the upper bearing of the disc motor. But the wire wore out problems and disc motor energy consumption will become more and more serious with the increase of the disc speed. The adding of the spring will also increase the cost of the product.

A more economic way to increase the drive insensitivity to external shock and

15   vibration disturbance is to develop a more robust and stable servo control system so that the laser spot would stay on track at all times. The Sliding Mode Control (SMC) techniques was first appeared in the early sixties. In this respect reference is made to: "J.J.E. Slotine and W. Li, "Applied Nonlinear Control", Englewood Cliffs, NJ: Prentice-Hall, 1991".

Due to its notable advantage of insensitivity to the disturbance and the

20   uncertain system, this invention extends SMC technique to the two-stage servo tracking system of optical disc drive to improve the product anti-shock performance. An estimator based discrete-time sliding mode controller has been developed to control the fine actuator not only to stabilize the system but also create highest robustness to external shock and vibration without critical requirement of accurately shock detection.

25   The schematic of compact disc mechanism can be generally depicted in figure 1. It consists of a turntable DC motor for the rotation of compact disc and two actuators with their mobile parts totally suspended on elastic elements to keep the laser spot in focus on the disc impressed surface and radially along the desired track, together with the sledge positioning system, which mainly carries out the seek action along the radial direction. In this

30   respect reference is made to: " Sorin G. Stan, "The CD-ROM Drive – A Brief System Description", Kluwer Academic Publishers, 1998". This electromechanical construction is usually designed as a two-stage or sledge-actuator servo system with the sledge doing the large displacements of the laser spot along the radial direction, and the focus and radial actuators (riding on the sledge) doing the fine displacements. The dynamic interactions

between radial and focus loops are relatively low. The radial and focus loops are usually designed and investigated separately in practical application. For the fine displacement, the focus and radial actuators are usually controlled by two separate PID controllers, thus creating two separate SISO (Single Input and Single Output) systems.

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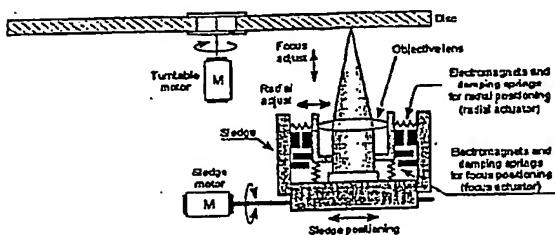
Figure 1 Schematic cross-section

Figure 2 illustrates the simplified block diagram of the spot position control

10 system during tracking for both focus and radial. The relative spot position error information is detected by the optical pick up G1(s) (here the measurement/sensor noise n(s) introduced during reading the feedback signal is included), it generates error signals e(s). The commonly used controller K(s) and the actuator driver G2(s) feed the system with the currents. H(s) represents the transfer function of the control current to the radial or focus spot position. d(s)

15 represents dynamic disturbances generated within the drive itself or from the external environment. This mainly includes radial and vertical track position deviations coming from disc unbalance, eccentricity, unroundness etc. and external disturbances of mechanical shocks and vibrations. They are presented as output disturbance $d_2(s)$ in the figure.

The reference signal r(s) predefined reference situated at the disc, is given by

20 the disc reflective laser in case of focus control loop, and by the centre of the read-out track in case of the radial loop. Due to the spiral shaped track of the optical disc itself, the laser spot along radial direction is controlled by the sledge-actuator radial loop with this PID-based controller to control the actuator fine displacements and the sledge positioning system to move the actuator outward at a slower space during tracking.

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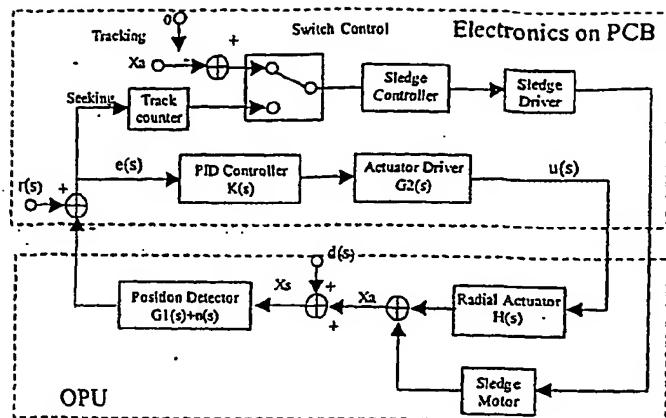
Figure 2. Simplified block diagram of the radial control

Disturbance coming from the deviation from the nominal position, rotation of
the disk, eccentricity and track irregularities etc. can be well regulated or controlled by the
present PID controller and some learning control algorithm during tracking. In this respect
reference is made to: "Steinbush, M. and G. Schootstra, "Filter, repetitive control system and
learning control system both provided with such filter", US Patent nr. 5740090, Apr.14,
1998", and to "Dotch, H.G.M., H.T.Smakman, P.M.J. Van den Hof, and M.Steinbuch,"
Adaptive repetitive control of a compact disc mechanism", Proc. 1995, IEEE Conference on
Decision and Control, New Orleans, Dec. 1995, pp.1720-1725", and to "Zhou Y., M.
Steinbush, and G. Leenkgnet, " Learning Feedforward Control for High-Spped CD-ROM",
Accepted by 1st IFAC Conference on.Mechatronic Systems, Sept., 2000"

The conventional PID controllers and the learning algorithms are however no
more effective to overcome the non-linear movement of the track on the disc relative to the
laser spot in the present of external shock and mechanical vibration disturbances. Robustness
to the modelling errors is also not guaranteed in the entire operating range. All these
uncertainties of the system lead to the application of SMC techniques to the servo system
design.

An estimator based SMC controller is then developed here to replace the
traditional linear PID controller for the optical disc drive servo system. Here, especially the
radial direction, which has proved to be the most critical direction, is described in detail. The
same principles are however also applicable to the focus loop.

It is thus an object of the invention to increase the shock resistance of a disk
drive apparatus without significantly increasing the cost of the apparatus.

To this end, according to the invention, a disk drive apparatus is defined which comprises: an optical pick-up unit movably mounted on positioning means for roughly positioning the optical pick-up unit with respect to a desired position on an optical disk, whereby, during operation of the apparatus, the optical pick-up unit is controlled by an

5   actuator for moving the optical pick-up unit relative to the positioning means in radial direction of the disk for fine positioning the optical pick-up unit with respect to the desired position on the optical disk, the actuator comprising a servo tracking controller for anti-shock control of the apparatus, the servo tracking controller comprising a state estimator, for estimating the radial position and velocity of the actuator, having an input responsive to a

10   radial tracking error derived from the optical pick-up unit; a shock detector for supplying a shock interrupt signal under control of information supplied by the state estimator to an input of the shock detector; a disturbance estimator; and a Sliding Mode Controller for supplying a control signal to the actuator based on information derived from the state estimator and from the disturbance estimator which receives said control signal and which receives information

15   from the state estimator, the Sliding Mode Controller also feeding back said control signal to the state estimator, the Sliding Mode Controller comprising a servo gain controller for setting a first gain setting and a second gain setting, and a selector for selecting either the first or the second gain setting under control of the shock interrupt signal.

The positioning means for roughly positioning the optical pick-up unit with

20   respect to the desired position on an optical disk is usually implemented by a sledge. Alternatively, a swing arm can be used. The optical pick-up unit is movably mounted on the positioning means so that it can be controlled by the actuator for fine positioning. Figure 3 shows the block diagram of the SMC controller which can for instance be implemented for the radial tracking servo system in a DVD player. It is to be noted that the

25   previously mentioned "servo tracking controller" is indicated as "Digital Servo Processor" in figure 3. The estimator based SMC controller blocks (indicated in the figure in dashed lines) for radial tracking within the servo DSP run at 22kHz, the servo processor clock frequency. It mainly comprises the following parts:

- State Estimator
30   - SMC controller
- Disturbances Estimator
- Shock Detector
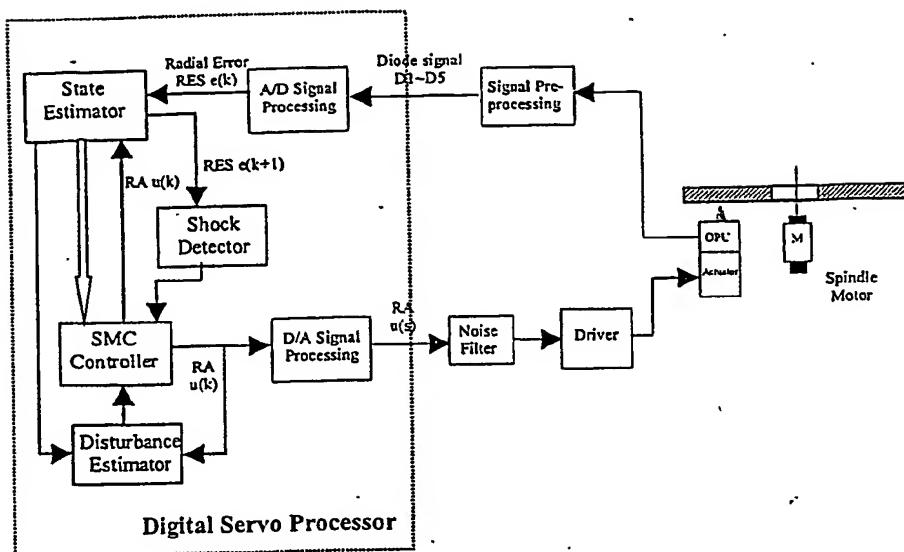
Figure 3. Block Diagram of the SMC anti-shock controller implementation

The estimator is used to estimate the entire state based on a measurement of
one of the state elements. For the optical disc drive digital servo, the estimator estimates the
actuator position, velocity and the control force based on the measurement of the radial error
signal.

Figure 4 shows an implementation of the state estimator. The state estimator
estimates radial actuator position $\hat{x}(k)$ and velocity $\hat{v}(k)$. The estimated states are then used in
the SMC controller to generate the actuator control signal u(k).
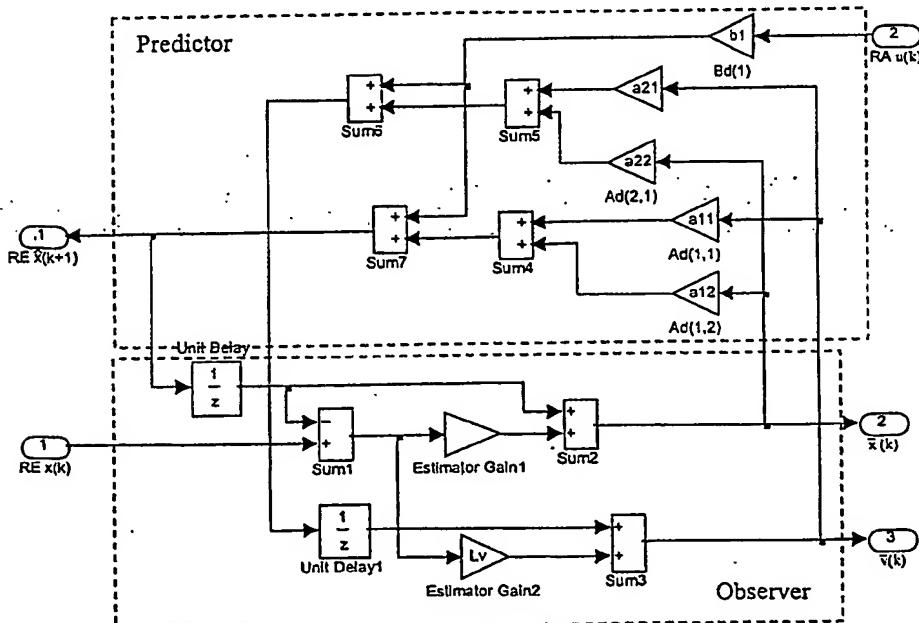
Figure 4. State Estimator model for SMC-based servo tracking control

The state estimator can be basically divided into two blocks: the state observer and state predictor. Radial position signal at time x(k) is sent to the observer block which estimates the current state of the actuator including the radial error $\bar{x}(k)$ and velocity $\bar{v}(k)$ of the actuator:

$$\bar{x}(k) = \hat{x}(k+1)/z + L_{res}(x(k) - \hat{x}(k+1)/z)$$
$$\bar{v}(k) = \hat{v}(k+1)/z + L_v(v(k) - \hat{v}(k+1)/z)$$

Where L_{res} and L_v are the estimator gain decided by the linear Quadratic Regulator (LQR) method. The estimated state together with the current control force u(k-1) are feed to the predictor to predictor/estimate the states of the actuator ($\hat{x}(k+1)$ and $\hat{v}(k+1)$)at next time k+1.

$$\hat{x}(k+1) = A_d(1,1)\bar{x}(k) + A_d(1,2)\bar{v}(k) + B_d(1)u(k)$$
$$\hat{v}(k+1) = A_d(2,1)\bar{x}(k) + A_d(2,2)\bar{v}(k) + B_d(2)u(k)$$

Where A_d (2x2) and B_d (2x1) are constant matrices and vector for the discrete model of radial actuator. They can be calculated from the specification of the actuator of the drive.

Assume that the disturbance like external shock and vibration is bounded and considerably slower than the sampling frequency of 22kHz which holds for the optical disc drive design by the specification. The value of disturbances at time k can be then considered to the value at time k-1, and can be calculated as:

$$\bar{d}(k) = \bar{x}(k) - A_d(1,1)\bar{x}(k-1) - A_d(1,2)\bar{v}(k-1) - B_d(1)u(k-1)$$

Figure 5 shows the implementing blocks of the disturbance estimator in the digital servo processor.
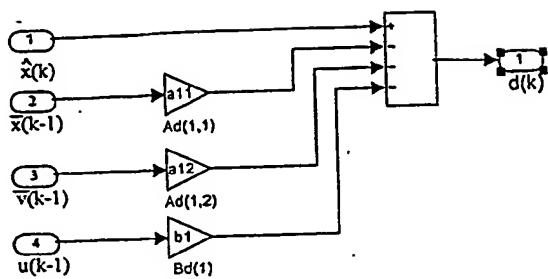
Figure 5. The disturbance estimator block

The sliding mode control is a robust non-linear control technique that replaces N-th order problems by equivalent 1st order problem. For radial tracking, the design objective is to keep $x(k) = x_d(k)$ for perfect tracking. (Here $x(k) = [x(k)\ v(k)]^T$ is the state vector of the radial actuator. The desired state of actuator/laser spot during tracking for fine actuator control loop is: $x_d(k) = [0\ \ 0]^T$ The radial error signal is defined as $e(k) = x_d(k) - x(k)$.) This is equivalent to that of remaining on the surface $S(k) = g_{res}x(k) + g_v v(k) = 0$ for all k>0. And this surface is called the sliding surface. The problem of tracking 2 dimensional vector $x_d(k)$ is now replaced by 1st order stabilisation problem in S. The goal is to design the control law such that it forces the system to converge into the sliding surface S(k) and then stay on the surface. For practical implementation, a finite-time reaching phase to the sliding surface existed due to unmatched initial condition of the states $x_d(0) \neq x(0)$. In order to account for modelling imprecision and disturbances (we do not know the system perfectly), and smoothing out the discontinuous control law, a boundary layer around the sliding surface is thus defined such that the system states should move to the sliding surface or its neighbourhood from any initial condition, and eventually converge to the surface or its neighbourhood. By the Lyapunov Stability Theory, the reaching condition to guarantee the existence of the sliding surface for the optical disc drive radial tracking control system is:

$S(k + 1) = (1 - \eta)S(k) - \varepsilon sat(\frac{S(k)}{\Phi})$. Where η is the positive constant determining the response in the reaching stage, and should probably decided according to the actuator sensitivity. Φ is a positive constant and is called the boundary layer thickness and decided by the maximum allowable radial error to keep tracking (which is usually set to ¼ of track pitch value). And ε

is the control gain of SMC. The control law to steer the actuator from any initial condition to the sliding surface is: (Can be deducted from the reaching condition and the drive model)

$$u(k) = k \cdot [\varepsilon sat(\frac{g_{res}\bar{x}(k) + g_v\bar{v}(k)}{\Phi}) + kk_1\bar{x}(k) + kk_2\bar{v}(k) + \bar{d}(k)]$$

Where kk_1 and kk_2 and k are coefficients determined by the actuator dynamic

5   characteristics and the SMC controller gains.

The sliding surface $(S(k) = gres.e(k)+gv.v(k) = 0)$ is a time-invariant surface in the state space. The constants "gres" and "gv" are such selected that $S(k)=0$ defines a stable sliding surface, where the actuator desired tracking position is invariant to disturbances

10   or dynamic uncertainties. This means by proper choosing the control force, a total invariance to disturbances and dynamic uncertainties can be achieved on this sliding surface according to the theory of variable structure systems.

The boundary layer refers to the surrounding area around the sliding surface. That is the neighborhood area around the desired tracking position of the actuator. It is such

15   defined that the discontinued (due to the function of sat()) control force to bring the actuator from any initial state or disturbed state back to the sliding surface is more smoothly.

The key point in the SMC controller design is to maintain certain performance characteristics within the linear region, such as phase margin, gain margin, and sensor noise

20   rejection by maintaining the same cross over frequency for the SMC controller as that of the traditional PID controller when operating within the boundary layer. When operating outside of the boundary layer, a higher SMC gain is used.

Figure 6 shows the SMC controller implemented model in the digital servo blocks.
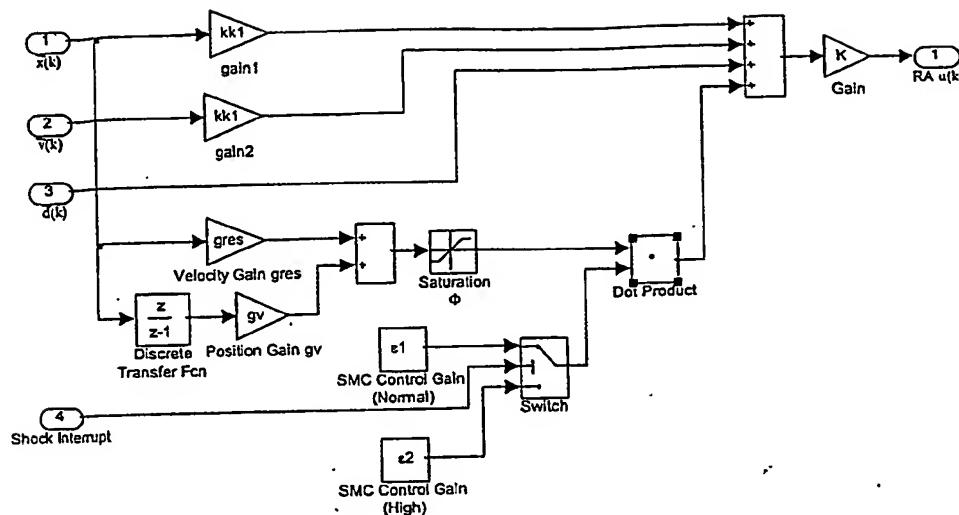
Figure 6. The SMC controller model

The shock detector comprises a low pass filter and a comparator. The

5   predicted radial error signal of next time e(k+1) from the state estimator is fed into the block

through a low pass filter of 850Hz and compared with the threshold value of ¼ of track pitch.

When the radial error information is greater than ¼ of track pitch, the shock detector will turn

on the high gain (the said second gain setting) SMC controller to pull the actuator back to the

centre of the track. When the shock detector detects that the radial error signal is less than the

10   ¼ of the track pitch value, the radial actuator control will then switch back to the normal gain

SMC controller (the said first gain setting).

The implementation block in figure 6 is the control law deducted from the

reaching condition that guarantees the existence of the stable sliding surface based on the

15   Lyapunov Stability Theory. It can be mathematically represented as:

$$u(k) = (gb_d)^{-1}\{\varepsilon\varepsilon \text{sat}\frac{\overline{S}(k)}{\Phi}) + g[((1-\eta)I + A_d)\overline{x}(k) + \overline{d}(k)\}$$

where bd and Ad are the constant matrix decided by the dynamic characteristics of the

20   actuator. As expressed in the below state space expression of the radial actuator:

$$x(k+1) = A_d x(k) + b_d u(k) + d(k)$$
$$y(k) = c_d x(k)$$

Switching from low gain to high gain actually makes that the controller has more power to bring the actuator back to the sliding surface, the desired tracking position, more quickly.
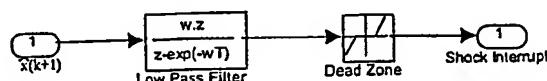

Figure 7. Shock Detector Model

If the system would always use high gain, there would be more power consumption which will shorten the chip and actuator life time. Too high gain servo control system will make the servo very sensitivity to disc defects like finger prints.

The high gain will be maintained until the radial error signal is reduced to less than 20% peak off-track value (i.e. 1/5 of track pitch). The HF information signal is on more reliable if the laser spot is more than 1/4 track pitch value. So in the SMC controller, we set the shock detector threshold to 1/5 of track pitch (that is about 20% peak off-track value) and switch the controller to high gain and immediately (one sample time delay) bring the radial error towards zero.

The gain switching is triggered by the observer-based shock detector which can predict the increasing trend of the radial error of more than 20% peak off-track one step ahead of the time and instantly take action to bring the actuator back to the track before it goes up.

As an example, experimental simulation is conducted on a DVD player. Figure 8 shows the Bode plot of the radial actuator for the drive. The initial value of the estimator gains are decided by the LQR method and the final gain values for the DVD player drive radial actuator are decided on pole placement by trial and error as:

$$L_{res}=1.3e4; \quad L_v=1.7241e6$$

The linear controller gains for the radial actuator during tracking for the DVD

player drive

are: $g_{res}=1.e2;$ $g_v=1.6e4;$ $\varepsilon=600$

Where, the control gain ε of SMC controller is decided that the whole system

gives about the same crossover frequency as that of the original PID controller, that is

2.2kHz, when the radial error is within the boundary area. Here, a boundary of 1000 is used,
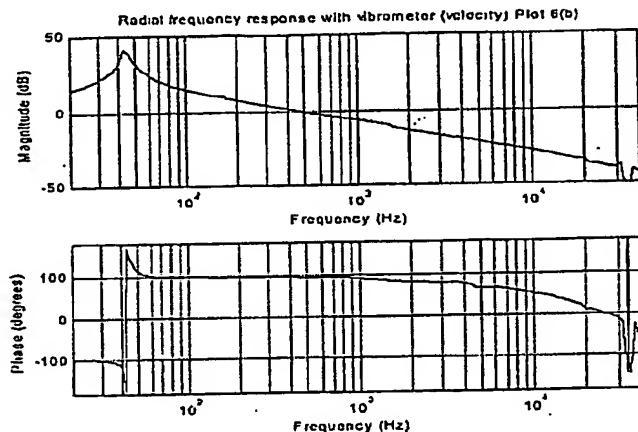
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Figure 8. Bode plot of the radial actuator for the DVD player drive

Corresponding to the 20% peak off-track (1/5 of track pitch value). When the

system is operating outside the boundary layer, like when experience shock/impact, and the

radial error intends to go to more than 1/5 track pitch, which is out of the control range of the

normal PID controller, the shock detector will immediately detect the case from the state

estimator one sample time ahead. The SMC controller will then switch to a higher SMC

control gain and brings the tracking error to the bounded area.

A formalised acceleration profile of a half-sine is chosen to represent the

typical shock disturbances in Audio/Video applications.

Figure 9 shows the simulated results of the radial error signal off-track value.

The peak off-track value of the original PID controller is 34.6% and it is reduced to 17.7%

when the SMC controller is used.
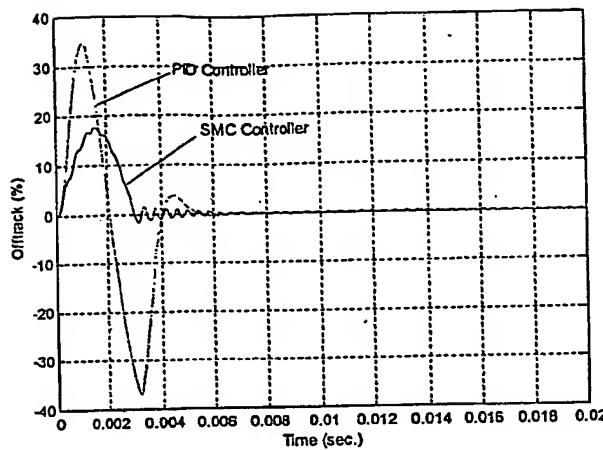
Figure 9. Simulation results of radial error signal off-track % with original PID
controller and SMC controller under shock

Figure 10 shows the radial error signal with and without SMC controller under
7gm/300ms with experimental data. The measured radial actuator sensitivity is around
0.65μm/V during playing at 1.2X DVD. The typical track pitch of DVD disc is 0.74 μm. As
can be seen from the plots, the peak off-track value without and with the SMC controller is
reduced from 28.1% to 8.7%.
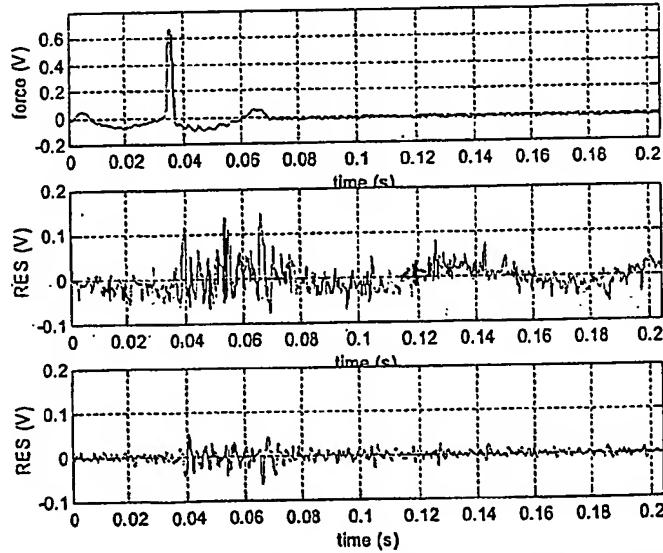
Figure 10. The experimental simulation results of radial error signal with and
without SMC controller

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From the above simulation and experimental results done on the DVD driver, the Estimator-based SMC with different control gain to compensate high vibration and shock shows a high level of immunity to unexpected external disturbances. Playability testing

5   results in radial direction shows that the shock performance specification can be improved from 4gm/300ms to 7gm/300ms. This method will improve the compact disc systems, especially those with high requirements on the anti-shock performance, like portable CD/DVD player, Car CD/DVD players, etc., without any increase of the material or process cost.

CLAIM:

A disk drive apparatus comprising an optical pick-up unit movably mounted on positioning means for roughly positioning the optical pick-up unit with respect to a desired position on an optical disk, whereby, during operation of the apparatus, the optical pick-up unit is controlled by an actuator for moving the optical pick-up unit relative to the

5   positioning means in radial direction of the disk for fine positioning the optical pick-up unit with respect to the desired position on the optical disk, the actuator comprising a servo tracking controller for anti-shock control of the apparatus, the servo tracking controller comprising a state estimator, for estimating the radial position and velocity of the actuator, having an input responsive to a radial tracking error derived from the optical pick-up unit; a

10   shock detector for supplying a shock interrupt signal under control of information supplied by the state estimator to an input of the shock detector; a disturbance estimator; and a Sliding Mode Controller for supplying a control signal to the actuator based on information derived from the state estimator and from the disturbance estimator which receives said control signal and which receives information from the state estimator, the Sliding Mode Controller also

15   feeding back said control signal to the state estimator, the Sliding Mode Controller comprising a servo gain controller for setting a first gain setting and a second gain setting, and a selector for selecting either the first or the second gain setting under control of the shock interrupt signal.